PB-217 405

COMBINED BIOLOGICAL AND CHEMICAL TREATMENT FOR PHOSPHORUS REMOVAL

Michael C. Mulbarger, et al

Robert A. Taft Water Research Center
Cincinnati, Ohio

1970

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

PB 217 405

Reprinted From . . .

Chemical
Engineering
Progress

SYMPOSIUM
SERIES

COMBINED BIOLOGICAL AND CHEMICAL TREATMENT FOR PHOSPHORUS REMOVAL

Michael C. Mulbarger and Donald G. Shifflett

United States Department of the Interior, Manassas, Virginia

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

VOL. 67, No. 107 1970 PAGES 107-116

11

COMBINED BIOLOGICAL AND CHEMICAL TREATMENT FOR PHOSPHORUS REMOVAL

Michael C. Mulbarger
and
Donald G. Shifflett

Liquid alum and sodium aluminate were utilized for phosphorus removal at 1.0 and 0.2 million gal./day activated sludge municipal wastewater treatment plants. Phosphorus removals were determined at aluminum to phosphorus ratios up to a limiting point which exhibited a minimum total soluble phosphorus residual of about 1.0 mg./liter. More efficient use of chemical and higher phosphorus removal efficiencies are obtained in a multistage activated sludge system. The type of activated sludge system also influenced chemical phosphorus removals. Excessive effluent suspended solids were found to be more a function of the volatile solids produced to aluminum added ratio than of exceeding a given aluminum to phosphorus ratio or aluminum dosage. The added chemical serves as a weighting agent in the activated sludge and fully compensates for the additional solids mass to be handled both in terms of system hydraulics and solids handling. Batch studies indicate that aluminum as alum will outperform iron as ferric chloride on a performance/cost basis and that the best point of addition is just before solids-liquid separation. The considerations involved in this type of phosphorus removal system are discussed.

The Manassas Field Station represents a cooperative effort by the Federal Water Quality Administration and Prince William County, Virginia, to investigate advanced waste treatment technology oriented to upgrading municipal wastewater treatment for nutrient removal (*1*). The effectiveness of liquid alum and sodium aluminate for phosphorus removal was evaluated in the County's 1.0 million gal./day activated sludge plant and a 0.2 million gal./day activated sludge pilot plant. The purpose of the investigation was to define the considerations and limitations involved in combining chemical phosphorus removal with activated sludge treatment.

FACILITIES

The two treatment facilities operate in parallel and receive screened, comminuted, and degritted wastewater from a common wet well. The 1.0 million gal./day plant, designed for biological phosphorus removal by luxury uptake (*2*), contains two activated sludge systems in series with intermediate solids separation by dissolved air flotation; waste solids from the second-stage system and digester supernatant are returned to the wet well. The main plant's anaerobic digesters receive waste solids from the flotation unit since it has no primary clarification and from the pilot plant's primary clarifier. The 0.2 million gal./day pilot plant, a scale-up of a nitrogen-phosphorus removal facility proposed by Barth and coworkers (*3*), contains three activated sludge systems, sequentially operated for rapid carbon removal, nitrification, and denitrification.

Liquid alum was applied to the beginning of the main plant's second-stage aerator. Sodium aluminate, unless otherwise noted, was applied to the beginning of the pilot plant's high rate or rapid carbon removal activated sludge system.

TECHNIQUES

The mean cell residence time (*4*), defined in this investigation as the pounds of solids under aeration divided by the pounds of solids wasted and lost in the ef-

U. S. Department of the Interior, Manassas, Virginia.

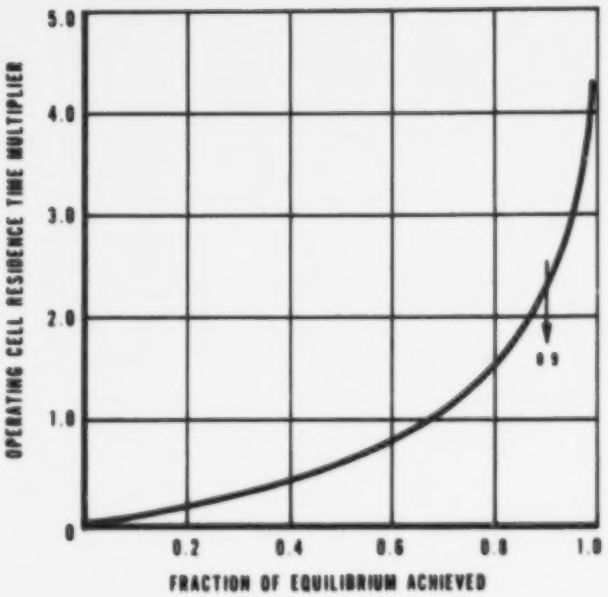

Fig. 1. Operating cell residence time multiplier versus fraction of equilibrium achieved.

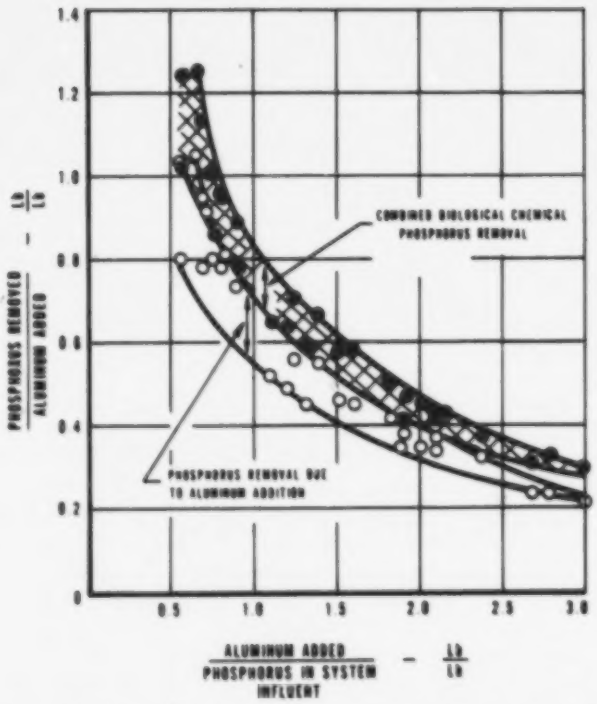

Fig. 2. Phosphorus removal performance envelopes; high rate activated sludge system.

fluent per day, was used as the means of activated sludge system control. A chronic problem in studying biological systems is proper conditioning prior to an investigative run. Figure 1 shows the relationship of operating cell residence time (CRT) multiplier (conditioning time/cell residence time) and fraction of equilibrium achieved; 90% equilibrium values are only achieved after a conditioning period of about 2.2 times the operating CRT. The data produced from a biological system can be misleading without proper conditioning, and with chemical additions this is especially true. In this paper approximate equilibrium values prior to the onset of the investigative period are presented.

All reported phosphorus values are for total phosphorus as determined after potassium persulfate addition and acid digestion (5). Calcium, magnesium, and sodium were determined by atomic absorption. Aluminum was measured with an Autoanalyzer. Turbidimetric sulfate and all other analytical measurements were performed according to *Standard Methods* (6). Soluble wastewater constituents are defined as those which pass through a Watman No. 5 filter.

In each study flow proportional samples were collected every 2 hr., composited, and analyzed daily. Sampling times in the seven-day studies were staggered to simulate a 24-hr. plug flow of wastewater through the plant. Sample composite periods began at the same time in longer study periods.

LIQUID PHASE AND EFFLUENT QUALITY

Problems with the 1.0 million gal./day plant's anaerobic digesters became apparent immediately prior to the initiation of liquid alum additions to the secondary aerator. Failure to achieve any appreciable solids-liquid separation in the secondary digester and the absence of primary clarification resulted in complete destruction of the plant's operational capability (2). Consequently, the phosphorus removal data collected over a two-month period were largely meaningless and are not presented.

Figure 2 summarizes the performance of the 0.2 million gal./day pilot plant's high rate activated sludge system receiving sodium aluminate for phosphorus removal. Daily performance of the unit is represented during four seven-day investigations. Overall and chemical phosphorus removal envelopes are presented. The lower envelope, phosphorus removal due to chemical addition, was found by subtracting the previously measured background or biological phosphorus removal rate [0.01 lb. of phosphorus removed per pound of chemical oxygen demand (COD) removed] from the total phosphorus removed per pound of aluminum added. Removals of phosphorus and COD are based upon the total phosphorus and COD in the system influent (primary effluent) minus the soluble phosphorus and COD in the system effluent. The results are specific for the study conditions, constant flow, and chemical feed over a 24-hr. period, and assumed constant biological phosphorus removal rate.

A more meaningful plot of chemical phosphorus removal is provided in Figure 3, where the phosphorus residual is the influent phosphorus minus the phosphorus

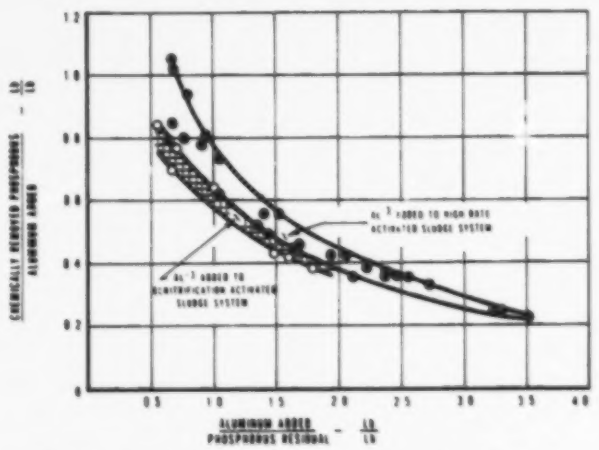

Fig. 3. Chemical phosphorus removal envelopes for two activated sludge systems.

removed biologically. It is apparent that chemical phosphorus removal within a biological system is not strictly independent of that biological system.

A probable soluble effluent phosphorus of 2.5 to 1.0 mg./liter is indicated in Figure 4 with the performance envelope from Figure 3 and an assumed phosphorus residual of 10 mg./liter. This curve also indicates that increasing the aluminum added to phosphorus residual ratio above two will not increase system performance.

Table 1 summarizes system performance with aluminum addition. The study numbers for the six seven-day studies are in chronological order, encompassing a period from December through March. Effluent deterioration due to high suspended solids was noted in Studies 3 and 4. Reestablishing a lower aluminum to phosphorus ratio in Study 5 resulted in effluent suspended solids about equal to that measured in Study 2, both an improvement over the control study. When using a previously satisfactory aluminum to phosphorus ratio and aluminum dose in the denitrification system, high effluent suspended solids

TABLE 1. SYSTEM PERFORMANCE WITH ALUMINUM ADDITION; LIQUID PHASE

Activated Sludge System		High Rate					Denitrification
Study No.		1	5	2	3	4	6
Equilibrium fraction at study initiation		0.99*	0.99*	0.92	0.98	0.99*	0.78
Cell Residence Time-days		1.2	1.6	2.8	1.8	1.4	5.0
Aluminum Dose	-mg/l	0	10.5	13.5	16.9	18.6	9.6
Al added / P influent	-lb/lb	0	0.8	1.2	1.8	2.0	1.0*
Al added / P residual	-lb/lb	0	0.9	1.5	2.0	2.5	1.1
Influent phosphorus	-mg/l	12.2	13.1	11.2	9.4	9.3	9.6
Effluent: total phosphorus	-mg/l	10.4	5.8	4.0	5.6	5.5	9.2
Total soluble phosphorus	-mg/l	9.8	3.2	2.6	1.6	1.4	3.7
Soluble aluminum	-mg/l	<0.1	<0.1	0.2	0.3	0.5	0.3
Suspended solids	-mg/l	51	37	38	80	100	75
Temperature	-°C	15.0	12.0	13.5	11.5	11.0	11.5
pH		7.2	7.2	7.1	7.2	7.2	7.2

*Based upon soluble phosphorus in system influent

reappeared. Soluble effluent aluminum concentrations of 0.3 mg./liter and higher coincided with high effluent suspended solids. The results indicate some phenomena other than solubility limitations of a precipitated aluminum-phosphate complex and simple overdose of coagulant. Reasoning that the biological solids may aid in chemical phosphorus removal through sorptive and/or exchange properties and that these sites may be exhausted with chemical overdose, Figure 5 was prepared.

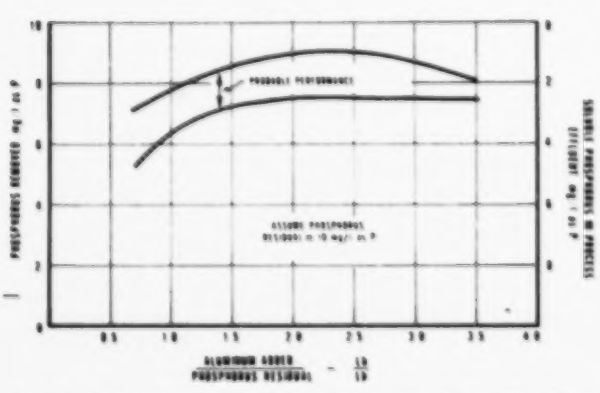

Fig. 4. Projected chemical phosphorus removal within a high rate activated sludge system.

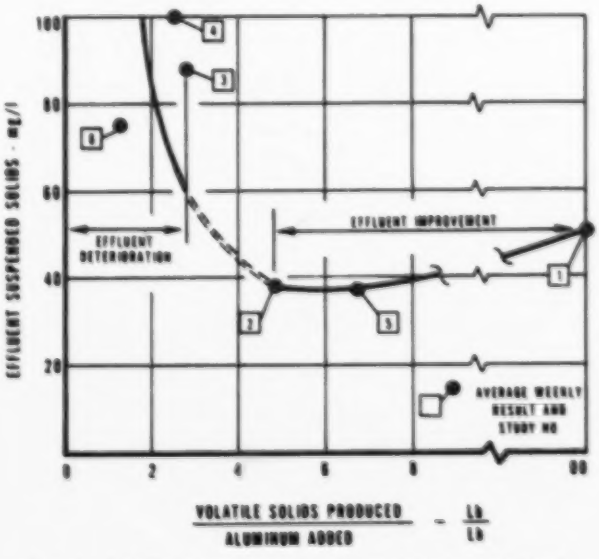
EFFLUENT DETERIORATION
EFFLUENT IMPROVEMENT
AVERAGE WEEKLY RESULT AND STUDY NO
VOLATILE SOLIDS PRODUCED / ALUMINUM ADDED - LB/LB

Fig. 5. Relationship between effluent quality, biological system, and chemical addition.

Figure 5 shows a trend relationship among effluent suspended solids, aluminum dose, and biological solids production. Net volatile solids production rates, pounds volatile suspended solids produced per pound COD removed, were assumed equal to those measured during the control studies for the high rate and denitrification activated sludge systems. This assumption was necessary because conventional volatile solids measurements (6) will also measure the loss of chemically bound water from any precipitated aluminum hydroxide.

At all sodium aluminate dosages, the effluent lacked the clarity customarily associated with activated sludge treatment. It is the authors' feeling that some secondary coagulant will have to be used to produce esthetically pleasing product water. In laboratory studies with a number of organic polyelectrolytes, two anionics (Nalco 675 and E-2339) produced excellent clarity at dosages of about 1 to 2 mg./liter.

SOLIDS PHASE AND HYDRAULICS

Figure 6 shows that the addition of 10 to 20 mg./liter of aluminum as sodium aluminate caused an additional 40 to 60 mg./liter of phosphorus laden solids to be produced. The additional solids production was calculated by subtracting the solids production rate, pounds of solids produced per pound of COD removed, measured in the control study from that measured during a study with aluminum addition. System hydraulics and volumetric requirements were unchanged since the aluminum additions caused a compensating increase in sludge density which is inversely proportional to the sludge volume index shown in Figure 6.

Figure 7 shows a total and soluble phosphorus profile of the main plant's secondary digester before and after

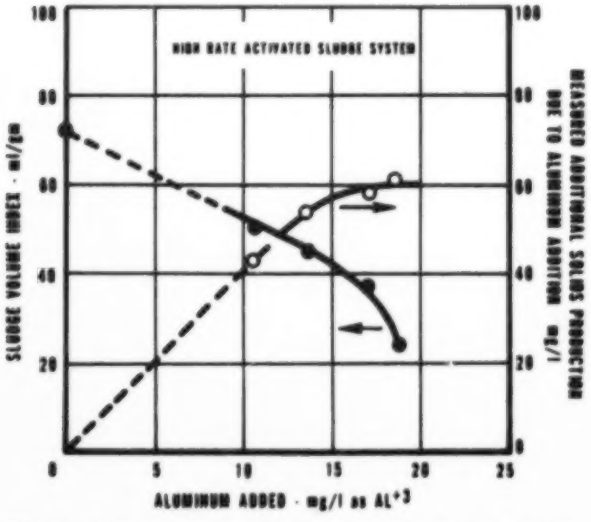

Fig. 6. Change in sludge volume index and additional solids production due to aluminum addition.

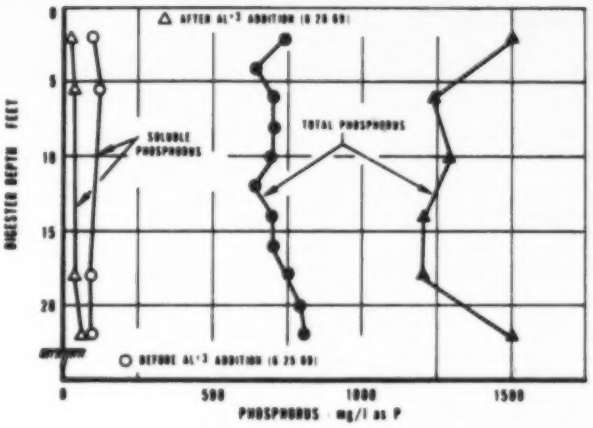

Fig. 7. Phosphorus profiles in the secondary digester before and after aluminum addition.

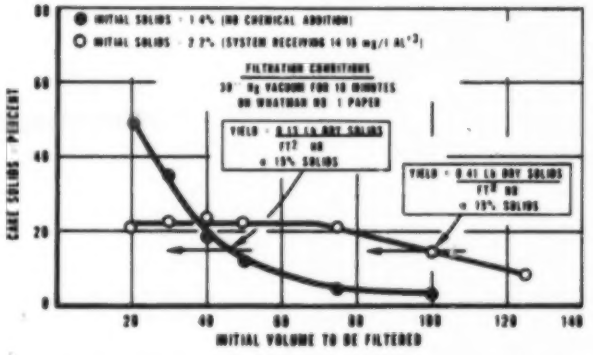

Fig. 8. Settled high rate activated sludge dewaterability with and without aluminum addition.

two months of liquid alum addition to the main plant; soluble phosphorus concentrations were reduced even though total phosphorus concentrations nearly doubled. When this digested sludge was applied to the sand beds, it exhibited superior drainability characteristics as compared to previous plant experience.

Filtration studies were performed on settled high rate activated sludge from the control study and from one of the aluminum addition studies. The relative result indicated in Figure 8 is that although filter yields may be substantially increased with aluminum-containing biological solids, they may not be dewatered to the same degree of dryness.

VERIFICATION STUDIES

Figure 9 describes the performance of the high rate activated sludge system receiving sodium aluminate for phosphorus removal over a 17-day period. Hydraulic conditions in this study are similar to those utilized in the previously reported investigations. Alkalinity and calcium and magnesium values are presented to show that

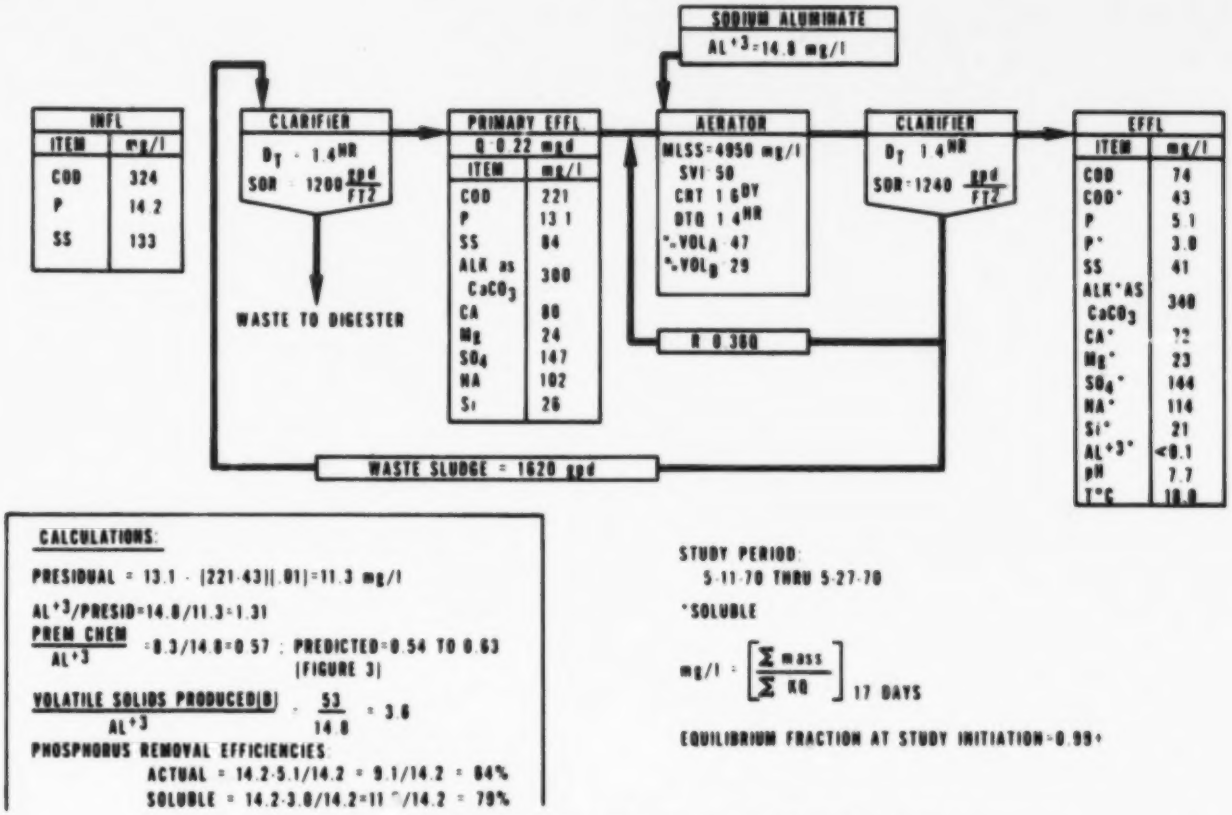

Fig. 9. High rate activated sludge system receiving sodium aluminate for phosphorus removal.

the Manassas water is alkaline and mineralized. Sodium values are shown since sodium aluminate adds about one part of sodium for each part of aluminum. Sulfate values are listed because of its influence upon chemical floc formation. Silica values are shown because sodium aluminate can be used for silica removal. Two methods for determining volatile solids are also presented: method A is by *Standard Methods* (6) and method B is with conventional ashing procedures preceded by acidification at *p*H 2, 10 min. of mixing, and then filtration (7); as can be seen, the mixed liquor suspended solids contain very little organic volatile matter. The calculations confirm previous observations from Figure 3. The volatile solids produced (calculated with acid pretreatment values) to aluminum added ratio may be somewhat lower than utilized in Figure 5, but indicates that the system was in a probable transition zone from effluent improvement to effluent deterioration. Actual phosphorus removal efficiency was 64%, whereas the removal efficiency based upon a soluble discharge was 79%.

Figure 10 shows the performance of the three-sludge system receiving sodium aluminate at both the high rate and denitrifying activated sludge processes for a 17-day period. Aluminum dosages were determined from previous plant experiences with volatile solids production and the relationship presented in Figure 5. Aluminum cannot be added to the nitrification system because it produces negligible quantities of volatile solids. Low aluminum dosages in the denitrification system are dictated because methanol is preferentially oxidized rather than synthesized. The reduction of the aeration contact time and cell residence time in the first-stage aerator resulted in a less settleable sludge which was attributed to a lack of bioflocculation. Nitrification and denitrification results are presented for information only and should not be interpreted without adequate explanation (*8*). For example, during one day of the study approximately ten times more digester supernatant than normal was returned to the plant's wet well which resulted in substantial ammonia breakthrough. Overall phosphorus removals in the three-sludge system were increased to 78 and 87% on an actual and soluble basis. More efficient use of chemical and higher phosphorus removal efficiencies is found with multisludge systems and split dosages of chemical.

MISCELLANEOUS CONSIDERATIONS

The considerations involved in combined biological-chemical treatment for phosphorus removal are listed in Table 2 and subsequently discussed.

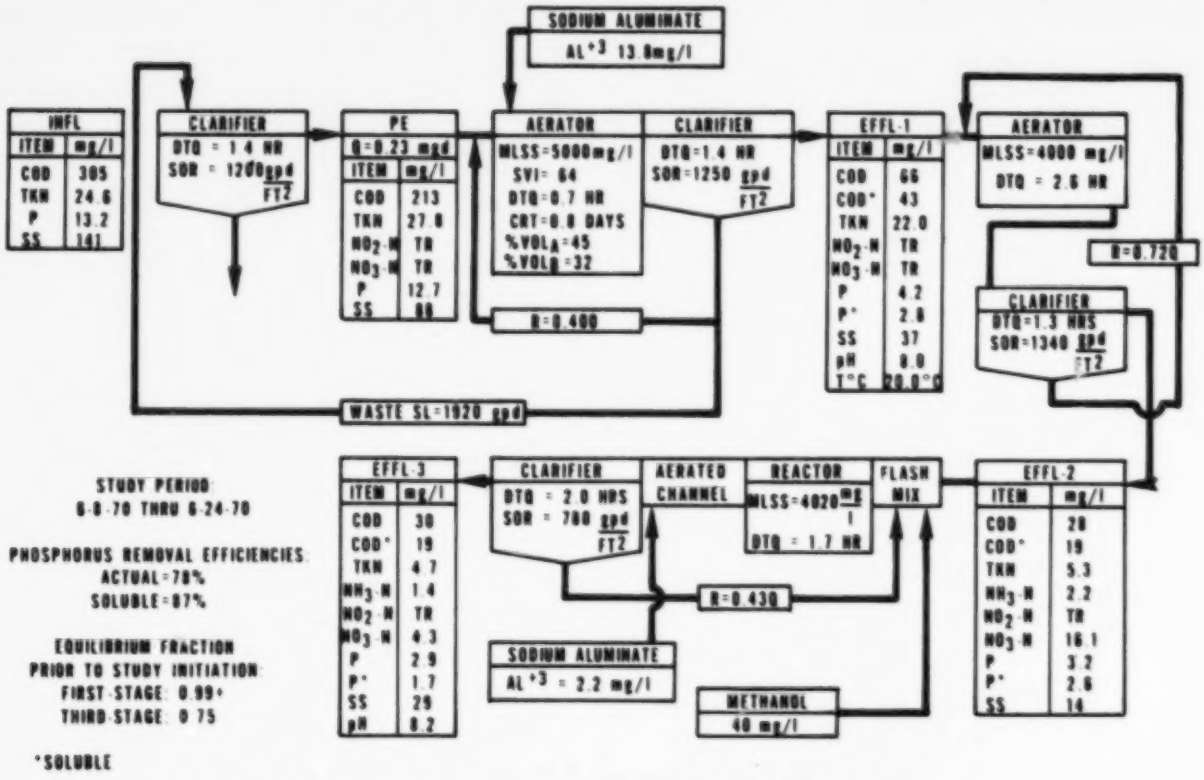

Fig. 10. Three-sludge system receiving sodium aluminate for phosphorus removal.

TABLE 2. CONSIDERATIONS INVOLVED IN COMBINED BIOLOGICAL AND CHEMICAL TREATMENT FOR PHOSPHORUS REMOVAL

A. WASTEWATER
   1. Phosphorus concentration
   2. Inorganic quality
   3. Organic quality
   4. Temperature
   5. pH

B. CHEMICAL SYSTEM
   1. Kind of coagulant
   2. Quantity of coagulant
   3. Point of addition
   4. Time of mixing and flocculation
   5. Violence of agitation
   6. Presence of nuclei

C. BIOLOGICAL SYSTEM

D. HYDRAULICS AND SOLIDS HANDLING

E. COST

WASTEWATER

Phosphorus Concentration. Unlike other phosphorus removal processes, the dominant variable for phosphorus removal by metal salt addition in municipal wastewater treatment may be substantially reduced if phosphorus concentrations are reduced.

Inorganic Quality. When using metal salts, the water's ionic composition and concentration have a strong effect upon the interrelationship of *p*H and phosphorus removal. Cations extend the useful *p*H zone in the basic region and anions extend the useful *p*H zone in the acid range (*15*). This occurs in accordance with the Schulze-Hardy rule: "The precipitation of a colloid is affected by that ion of an added electrolyte which has a charge opposite in sign to that of the colloidal particles, and the effect of such ion increases markedly with the number of charges it carries." The performance of a metal ion or electrolyte for phosphorus removal should improve with increasing water hardness. Alkalinity considerations (see later) are also important.

Organic Quality. Different substrates or organic compounds are oxidized for free energy and synthesized by activated sludge at different rates. The net amount of biological solids produced is influenced by the system's design as well as the quantity and type of substrate.

Obviously, a wastewater with a high organic concentration applied to an activated sludge system designed for maximum solids production will increase the phosphorus removal by background of biological mechanisms.

Temperature. Organism activity and type are influenced by liquid temperature. Similarly, the completeness of a chemical reaction is influenced by temperature. Colder temperatures should reduce phosphorus removal efficiencies.

pH. Wastewater *p*H and process *p*H are important considerations when adding metal salts to a biological process. The optimum *p*H for aluminum addition is 5 to 6 and, with iron, about 4.5 to 5.5, whereas a biological system performs most efficiently between 6 and 8. Nitrification is most easily achieved above *p*H 7 (9). There exists in combined biological-chemical treatment for phosphorus removal a conflict and, in turn, a compromise in *p*H goals. Figure 11*A* shows the effect of *p*H upon the molar phosphorus removal effectiveness of aluminum and iron. Above *p*H 8, phosphorus removal is occurring through the formation of an insoluble calcium-phosphate complex via the natural hardness of the Manassas water. Figure 11*B* shows that the optimum *p*H zone for nitrification is the worst for phosphorus removal through metal salt addition.

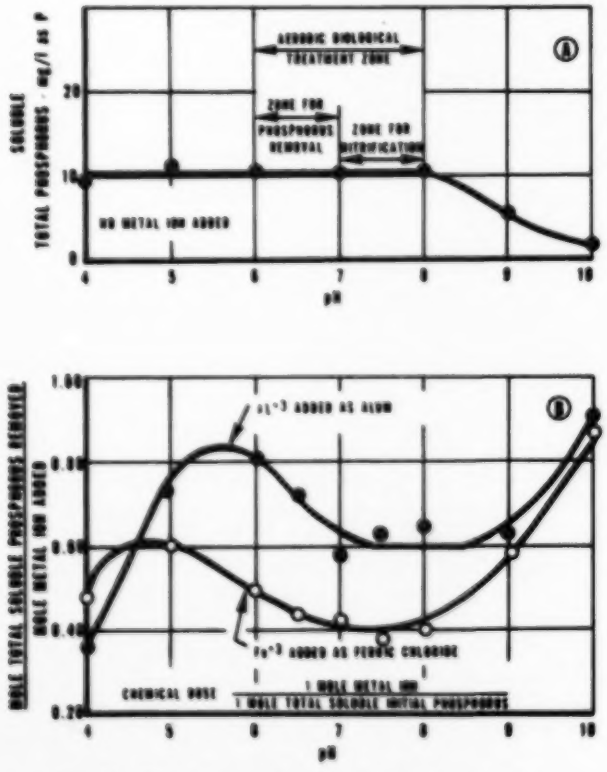

Fig. 11. Effect of *p*H on phosphorus removal from a final effluent.

CHEMICAL SYSTEM

Kind of Coagulant. The selection of a metal ion and salt for phosphorus removal involves a multitude of considerations. Any commercial chemical or industrial waste stream bearing available aluminum or iron has potential application. The representative compounds of iron and aluminum listed in Table 3 introduce extraneous

TABLE 3. METAL SALT COMPARISON

Metal Salt	Bulk Delivered Price at	Extraneous Ion Introduced		Alkalinity Loss
	Dollars	Pounds		Pounds as $CaCO_3$
	per pound of metal ion			
Liquid Sodium Aluminate (AL_2O_3)	0.69	Na^+	0.85	None
Liquid Alum (AL_2O_3)	0.32	$SO_4^=$	5.3	5.6
Ferric Chloride (Fe_2O_3)	0.23	Cl^-	0.85	2.7

ions into solution, each of which can be considered a pollutant in its own right (*10*). Ferric chloride and alum cause a loss of alkalinity, and without an adequate buffering capacity in the wastewater substantial *p*H reductions may occur unless an additional alkaline source as lime is added to the water. Cost as well as the proven coagulation aid derived from the sulfate ion (*11*) makes alum the most attractive aluminum source, even though in low alkaline waters additional alkalinity may have to be added.

The mechanism of phosphorus removal and coagulation by metal salt addition in a biological system is through a combination of precipitation, adsorption, exchange, and agglomeration as influenced by the *p*H and ionic composition of the water (*12* to *19*). The complexity of these reactions makes each water and system unique.

Quantity of Coagulant. Figure 12 shows the soluble total phosphorus residual as a function of the metal ion dose with Manassas raw wastewater, mixed liquor from a high rate activated sludge system which was not receiving chemical additions and final effluent. Phosphorus removal increases with increasing dose to a limiting residual of about 1.0 mg./liter as P for the raw wastewater and final effluent and less than 0.1 mg./liter as P for the aerator mixed liquor. An apparent approximate phosphorus residual of 1.0 mg./liter was indicated in the previously conducted aerator studies with sodium aluminate (Figure 4). It was reasoned that the residual of less than 0.1 mg./liter was actually fictitious and not due to the added sulfate from the alum, but rather that chemical equilibrium with the aerator's volatile solids adsorptive and/or exchange sites had not been obtained. It is felt that a total soluble phosphorus residual of about 1.0

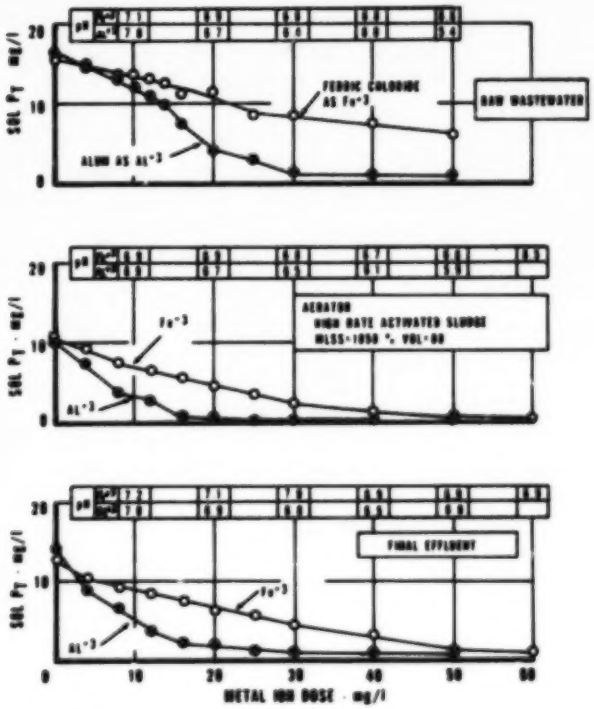

Fig. 12. Soluble total phosphorus residual versus metal ion dose.

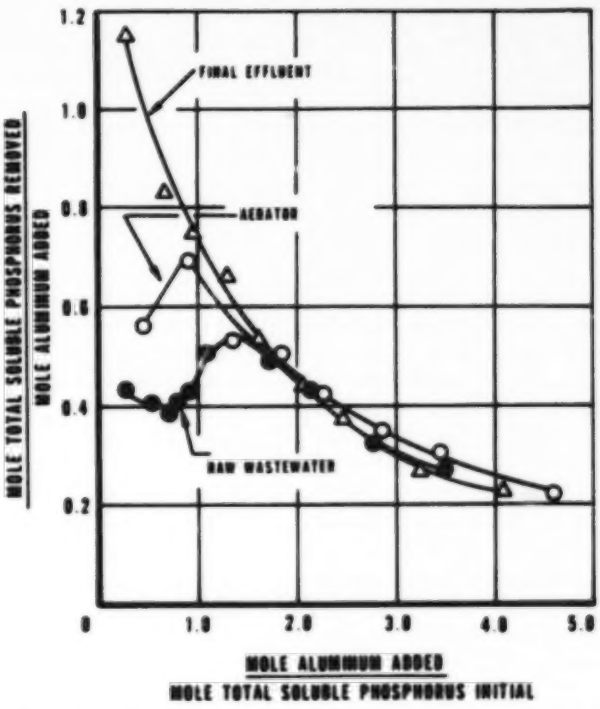
FINAL EFFLUENT
AERATOR
RAW WASTEWATER
MOLE TOTAL SOLUBLE PHOSPHORUS REMOVED / MOLE ALUMINUM ADDED
MOLE ALUMINUM ADDED / MOLE TOTAL SOLUBLE PHOSPHORUS INITIAL

Fig. 13. Influence of point of addition on phosphorus removal with aluminum.

mg./liter is a practical limit for the Manassas wastewater receiving metal salts for phosphorus removal.

Point of Addition. In the batch studies on a weight, molar, and cost basis, aluminum as alum consistently achieved a greater phosphorus removal than iron as ferric chloride at all the potential points of application indicated in Figure 12. Figure 13 shows the influence of the point of addition on the molar effectiveness of the added aluminum. The period before the hump which was noticed with aluminum additions to the raw wastewater and aerator mixed liquor is thought to be due to presence of unhydrolyzed phosphorus and the occurrence of competing side reactions with the aluminum. Aluminum and iron are known to form insoluble heavy salts with certain hydrophilic colloids such as detergents and soluble proteins and their degradation products (*15*), all of which would be present in raw and partially stabilized wastewater. At molar aluminum to phosphorus ratios of less than 1:1, there is an obvious advantage in phosphorus removal derived by adding the chemical to a well-stabilized biological effluent, whereas at molar ratios of 1.5:1 and above, no point of addition advantage is apparent. Similar characteristics were noted with ferric chloride. In combined biological-chemical treatment for phosphorus removal, the ideal point of chemical addition would be just before mixed liquor solids-liquid separation.

Time of Mixing and Flocculation. Coagulation is a time-concentration phenomenon. Concentration increases the opportunity for contact and decreases the time required for floc formation. In combined biological-chemical treatment for phosphorus removal, larger chemical dosages than encountered in water treatment are utilized; therefore the mixing time requirement is reduced and chemicals can be confidently added to the end of the aerator just before solids-liquid separation.

Violence of Agitation. Utilization of activated sludge mixing tanks for chemical mixing and flocculation is a compromise. Typically, a diffused aeration system will have a velocity gradient of over 100 ft./(sec.)(ft.) and a mechanical aeration system's velocity gradient will be much higher. Experience has shown in water treatment that a velocity gradient greater than 75 ft./(sec.)(ft.) will result in the onset of chemical floc disintegration (*16*). Undoubtedly chemical floc disintegration does occur in activated sludge tanks and, because of solids recycle, it is unavoidable. Floc disintegration and coagulant overdose both lead to degradation in product water clarity. In new design situations, it may be advantageous to provide a brief period of gentle solids agitation prior to solids separation to promote reflocculation of the chemical-biological solids.

Presence of Nuclei. The return sludge stream of an activated sludge system receiving metal salts undoubtedly is helpful for inorganic floc growth by pro-

viding precipitation nuclei which aid in the formation and growth of new floc.

BIOLOGICAL SYSTEM

A system with a low cell residence time, such as high rate activated sludge treatment, maximizes cellular production and in turn biological phosphorus removal. This type of system also assures that an adequate volatile solids to aluminum added ratio is maintained (Figure 5) and maximizes the performance of a combined biological-chemical treatment system for phosphorus removal (see Figure 3 and Table 1 which compare the performance on high rate and denitrifying activated sludge systems with cell residence times of about two and five days). There is a limit, however, in the reduction of cell residence and hydraulic contact time that is practical; in comparing Figures 9 and 10 it is seen that the high rate system in Figure 10 produced a poorer settling sludge as measured by the SVI. Also, as previously mentioned in the discussion of the chemical system, higher phosphorus removals are indicated with a greater degree of wastewater stabilization. It is felt that a high rate system with a CRT of 2.0 ± 1.0 days and a hydraulic contact time of about 1 to 1.5 hr. is the practical limit for design.

HYDRAULICS AND SOLIDS HANDLING

The addition of metal salts to the activated sludge system serves as a weighting agent for the sludge floc which rapidly settles. This effect increases with increasing metal dosage and compensates for the additional sludge mass resulting from chemical addition. This results in no additional hydraulic capacity requirements and allows the potential use of higher hydraulic loading rates in solids-liquid separation processes. The data also indicate that performance of physical dewatering units will be increased in terms of solids yield (Figure 8) but that cake dryness may be affected.

COST

The additional cost for phosphorus removal in a combined biological-chemical system is largely the cost of the chemical. The required capital facilities would be chemical storage vessels, dosing pumps, and process control equipment. Power and additional operational labor would be negligible. Metal salt cost will be determined by the desired phosphorus removal up to a limiting soluble phosphorus residual. There will also be a cost for organic polymer and possibly lime for alkalinity control.

CONCLUSIONS

The data reported in this investigation cannot be interpreted as an optimized performance of a combined biological-chemical phosphorus removal system. The results are specific for the Manassas wastewater with a pilot plant receiving nearly constant flows and chemical dosages over all study periods. The chemical used, sodium aluminate, and point of addition, beginning of aeration, were not optimal for the wastewater and system.

The results reported indicate the following:

1. Chemical phosphorus removal within a biological system is influenced by the biological system; this is largely attributed to its volatile solids production which apparently provides phosphorus adsorption and/or exchange sites.

2. Phosphorus removal by metal salt addition is limited to a soluble residual of about 1.0 mg./liter as P. Split treatment of chemical dosages in a multisludge system will result in the most effective use of chemical.

3. Excessive effluent suspended solids is due more to failure to maintain a correct volatile solids produced to aluminum added ratio than either aluminum to phosphorus ratios or strict overdose of chemical. At all doses of sodium aluminate, the effluent lacked clarity; it is felt that either organic polymers and/or filtration will have to be provided to assure esthetically pleasing product water.

4. The increase in sludge density derived from metal salt addition compensates for the additional solids production, allows the use of higher hydraulic loads upon solids separation processes, and necessitates no additional hydraulic capacity.

5. When using aluminum, no solubilization of phosphorus occurs during anaerobic digestion.

6. Chemical-biological sludge dewatering characteristics are such that cake yields will be substantially increased, although the cake may contain more moisture.

7. Batch studies have shown that aluminum as alum is more effective than iron as ferric chloride on a molar and cost basis for the Manassas conditions. In addition, these studies have shown the influence of wastewater stabilization upon effective use of chemicals and suggest the most favorable point of addition as just before solids-liquid separation.

FUTURE STUDIES

Future studies with the Manassas pilot plant will be oriented to seasonal process changes. The point of chemical addition has been changed to just before solids-liquid separation. Liquid alum has been selected for long-term evaluation. A multi- or mixed-media filter will be used to polish the system's final effluent. Programmed 24-hr. flow and chemical feed variability will be utilized and phosphorus removal will be studied with chemical additions to the high rate activated sludge system and the denitrification system and/or tertiary filter.

ACKNOWLEDGMENT

Calcium, magnesium, sulfate, aluminum, and silica determinations were performed by the Analytical Services Section

of the Robert A. Taft Water Research Center. Appreciation for their time and effort is expressed to the staff of the Greater Manassas Sanitary District's Water Pollution Control Facility: Messrs. Huffman, Murphy, English, Franklin, Hockett, Jenkins, and Walker.

The research upon which this publication is based was performed pursuant to Contract WA 66-19 with the Federal Water Quality Administration, U. S. Department of the Interior.

LITERATURE CITED

1. Mulbarger, M. C., G. L. Page, Jr., O. W. Yates, Jr., and N. C. Sharp, *Water Wastes Eng.*, 6(4), 46 (1969).
2. Mulbarger, M. C., D. G. Shifflett, M. C. Murphy, D. D. Huffman, paper presented at 42nd Ann. Conf. Water Pollution Control Federation, Dallas (Oct. 1969).
3. Barth, E. F., R. C. Brenner, and R. F. Lewis, *J. Water Pollution Control Federation*, 40(12), 2040 (1968).
4. Jenkins, D., and W. E. Garrison, *ibid.*, 40(11), 1905 (1968).
5. Gales, Jr., M. E., E. C. Julian, and R. C. Kroner, *J. Am. Water Works Assoc.*, 58(10), 1363 (1966).
6. "Standard Methods," 12th edit., Am. Public Health Assoc., New York (1965).
7. Humenick, M. J., and W. J. Kaufman, paper presented at 5th Intern. Conf. Exhibition Water Pollution Res., San Francisco (July 1970).
8. Mulbarger, M. C., paper presented at 43rd Ann. Conf. Water Pollution Control Federation, Boston (Oct. 1970).
9. Downing, A. L., H. A. Painter, and G. Knowles, *J. Inst. Sew. Purif.*, Pt. 2, 130 (1964).
10. McKee, J. E., and H. W. Wolf, eds., *Publ. No. 3-A*, California Water Quality Control Board, Sacramento (1963).
11. "Water Quality and Treatment," 2nd edit., Am. Water Works Assoc., New York (1951).
12. Lea, W. H., G. A. Rohlich, and W. J. Katz, *Sewage Ind. Wastes*, 26(3), 261–275 (1954).
13. Stumm, W., in "Advances in Water Pollution Research," W. W. Eckenfelder, ed., Vol. 2, pp. 216–229, Macmillan, New York (1964).
14. Farrell, J. B., B. V. Salotto, R. B. Dean, and W. E. Tolliver, *Chem. Eng. Progr. Symp. Ser. No. 90*, 64 (1968).
15. Sawyer, C. N., "Chemistry for Sanitary Engineers," McGraw-Hill, New York (1960).
16. Fair, G. M., and J. C. Geyer, "Water Supply and Waste-Water Disposal," Wiley, New York (1961).
17. Kaufman, W. J., "Colloid Chemistry in Water Coagulation," abstracted from "The Removal of Radioactive Anions by Water Treatment," by W. J. Kaufman, U. S. Atomic Energy Commission, NYO-1571 (1951).
18. Tenny, M. W., and W. J. Stumm, *J. Water Pollution Control Federation*, 37(10), 1370–1387 (1965).
19. Eberhardt, W. A., and J. B. Nesbitt, *ibid.*, 40(7), 1239–1267 (1968).

RECEIVED
NATIONAL TECHNICAL
Jan 15 1973
INFORMATION SERVICE